Workshop Micro- and Nanosystems (MNS) Horizon 2040
Held on June 21, 2009 in Denver, CO

Final Report: Project Activities

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The goal of the Micro- and Nanosystems Horizon 2040 Workshop was to define a vision for future micro- and nanosystems (MNS) research in four specific domains of potentially great societal impact, namely (1) environmental sensing/monitoring, (2) infrastructure monitoring and homeland security, (3) health care, and (4) energy/power. The workshop was intended to identify engineering research priorities for the micro- and nanosystems community from a top-down perspective, based on recognized potential societal impact. The workshop included an opening plenary session featuring short presentations on each of the four specific domains of interest and subsequent extended focused discussion by breakout groups that address associated issues for each domain in some detail (see Fig. 1 for Workshop Program). The objectives were to define visions with respect to potential capabilities and applications for micro and nano systems in the domains of interest for 2040, identify fundamental challenges that must be addressed to realize these visions and recommend associated research priorities.

8:15 AM	**Welcome and Opening Remarks** Dr. William E. Snowden (SPC/Consultant) Dr. Yogesh Gianchandani (NSF/ENG/ECCS)
8:30 – 10:00 AM	**Short Presentations by Panel Co-Chairs** **1. Environmental Sensing/Monitoring** Dr. Richard Brown (University of Utah) Dr. Ana Barros (Duke University) **2. Infrastructure Monitoring and Homeland Security** Dr. Gary Fedder (Carnegie Mellon University) Dr. Andy Nowak (University of Nebraska)
10:00 – 10:15 AM	Break
10:15 – 11:45 AM	**Short Presentations by Panel Co-Chairs** **3. Health Care** Dr. Nitish Thakor (Johns Hopkins University) Dr. Yu-Chong Tai (California Institute of Technology) **4. Energy/Power** Dr. Mark Shannon (University of Illinois) Dr. Z.L. Wang (Georgia Institute of Technology)
11:45 AM – Noon	**Discussion: Panel Guidance**
12:15 – 3:00 PM	**Individual Panel Discussions and Preparation of Panel Report-Back Briefing**
3:15 – 4:45 PM	**Panel Report-Back Briefings and Discussion**

	Environmental Sensing/Monitoring Infrastructure Monitoring and Homeland Security Health Care Energy/Power
4:45 – 5:00 PM	**Closing Remarks** Dr. Yogesh Gianchandani, NSF Sponsor
5:00 PM	ADJOURN

Figure 1: Workshop program.

On the invitation of Prof. Yogesh Gianchandani, at that time a program director in the NSF ECCS division, the workshop brought together national and international panelists selected for their specific expertise in one of the four noted domains. The workshop outcomes and panel recommendations were summarized in a report to the National Science Foundation. A summary of the workshop recommendations has been presented in [1]. The workshop was held on Sunday, June 21, in conjunction with the 15th International Conference on Solid-State Sensors, Actuators & Microsystems (also known as the Transducers 2009 Conference), which is sponsored by the IEEE Electron Devices Society.

In the following, the workshop outcomes are briefly summarized [1] and the participant support from this NSF grant is highlighted. Details on the recommendations given by the panel can be found in the report submitted to the NSF ECCS program director Yogesh Gianchandani.

1. Workshop Outcomes [1]

For the road-mapping exercise directed towards research in engineered systems, a number of questions were identified that apply to every of the four topical domains. These included, for example:

a. What is the current state of the art within the research and commercial sectors? What are the scientific and technological concepts that currently motivate the use of MNS in each of the four topical disciplines?
b. Looking ahead to 2040, what are the potential capabilities and applications for MNS in these topical disciplines? In addressing this question, it is helpful to identify the following: what is the anticipated function and utility of the system; who are the potential customers – i.e., who will pay for the product, and who will use it; how many people may be impacted by the technology, both directly and indirectly; what kind of cost and performance targets are necessary and how does the MNS solution compare to other approaches in these respects; and what is the primary motivation for utilizing MNS in these scenarios?
c. What are the scientific and technological challenges that must be addressed to realize the vision for 2040? In the MNS context, for example, answers to this question may separately address transduction modalities for sensing and actuation; design methods, including modeling and simulation; manufacturing technologies, including the availability of materials, device processes, and packaging; interface circuits, including signal conditioning and communication circuits; data storage, processing, and mining;

system integration; calibration, testing, and reliability.

d. What are the pathways for addressing the scientific and technological challenges that were identified? Given the goals, what should be the research priorities for the coming 5-year period (Horizon 2015), the following 10-year period (Horizon 2025), and the subsequent 15-year period (Horizon 2040)? While recognizing that the boundaries between these periods are fluid, and that the discoveries and innovations in the earlier periods will have an impact on later work, is it possible to perform a triage of funding priorities for these periods? Can we identify the resources that are needed – access of equipment and facilities, manpower, standards, etc. – that are not on the necessary trajectories?
e. Is there a role for alliances – internationally linking universities, government-supported research laboratories, and industry – in executing this vision? If yes, then what is needed to facilitate these alliances?

It should be recognized that not all of these questions have clear or definitive answers. To the extent that a consensus emerges for some of these questions, of course it can provide guidance not only to organizations that control research and development funds, standards, and public policy, but also to researchers, publishers, and educators. An on-going, informed debate about the issues that fail consensus can be just as beneficial.

The recommendations of the *NSF MNS Horizon 2040 Workshop* are presented below in a highly abbreviated form. The panels recognized that, given the breadth of each of the topical domains, these recommendations are only a starting point, and are expected to evolve as the debate progresses.

Environmental Sensing/Monitoring

With growing threats to the environment posed by global warming, worldwide population growth, and increasing industrialization, there is a need for a better understanding of the changing conditions of both atmospheric and aquatic environments. A variety of chemical, physical, and biological sensors are necessary for measurements that are distributed in both space and time. Some of these applications demand power sources that operate over prolonged periods of deployment in remote or inaccessible locations, perhaps by scavenging energy from the environment. Further, environmental monitoring systems must be configured in a manner that permits the data to be collected, processed and interpreted in an intelligible and timely manner. The panel reviewed some of the opportunities and challenges that lie ahead, and recommended the following priorities.

a) Horizon 2015:

1. Better low-cost sensors for detecting/analyzing microbes (presence, function, activity)
2. MNS for complex mixtures of stressors (air, water, food; chemical and physical)
3. System integration, including location and timing (potentially GPS); algorithms for intelligent sensing
4. Research to reduce manufacturing cost, increase reliability, reduce calibration frequency (self-calibration)
5. Standards and protocols for implementation

6. Packaging, barrier/interface properties, performance of sensors in harsh environments

b) Horizon 2025:

1. Nanoparticle sensors (sensors/systems for detecting/analyzing nanoparticles)
2. MNS aerosol (particle) monitors that provide size, count, and composition (sub-micron to nanometer size)
3. Personal exposure monitors - combinations of sensors
4. Comprehensive water quality monitoring systems
5. Advanced sensors/networks for use in complex environments containing numerous analytes (e.g., toxic industrial contaminants, and complex biological systems)

c) Horizon 2040:

1. Zero-impact (readily retrievable or degradable) MNS for oceanic, arctic, and other environments
2. Continued progress in advanced sensors for use in complex environments containing numerous analytes

Health Care

Health care applications have inspired research in MNS for many decades. Research directed at implantable neural probes, retinal prostheses, and various other types of sensing and stimulating systems, has often set the bar for miniaturization, power-efficiency, and reliability. Research in microfluidics is paving the way for transformational changes in diagnostic tools for applications ranging from blood sorting to DNA analysis. Given this rich history and the sizable quantity of current research, what are the opportunities for MNS that can be envisioned? The roadmap must anticipate emerging challenges in healthcare, given demographic, economic, and environmental trends. For example, the average age of the population is rising in many developed nations, whereas the incidence of diabetes, cardiac disease, and lung disease is rising in many developing nations. The panel recognized that MNS provide a compelling vision for health care. By 2040, we may have MNS that contribute to the following:

- Personalized medicine: genetic tests, profiling, and developing biomarkers are carried out at individual levels
- Synthetic biology: building from the basic building blocks, DNA, proteins and cells
- Instruments for studying proteins and subcellular phenomena, and for constructing genetic networks from and within single cells
- Instruments for detecting, isolating and treating single cells, resulting in methods for early detection of cancers and markers for single tumor cells and mutations
- A merger of stem cell and tissue engineering resulting in artificially constructed organs grown from the body's own machinery, augmented by biomimetic or biologically inspired synthetic materials
- Synthetic or "synflex" materials that lead to smart catheters and smart blood vessels, blurring the boundaries between the body part and the synthetic part

With regard to *in vivo* systems, the perception was that future advances with come from merging biological systems with MNS and information systems. The hope is that these will lead to intelligent implantable devices with the ability to sense and act autonomously, e.g., insulin pumps that self-regulate; deep-brain stimulators that sense neuro-chemical and electrical activity;

and implantable devices that are both diagnostic and therapeutic, providing an interface to the outside world. With regard to *in vitro* systems, the hope is for more advanced composite systems (analytical lab-on-chip systems) that accommodate pico and femto liter samples, adapt to the chemical requirements, and incorporate purification, separation and detection. For analytical microsystems, sample preparation can be a significant challenge, so the ability to perform functions such as whole blood analysis at the point of care (using low-cost devices that are mass produced by micro and nanofabrication technologies) is also seen as important. The systems may utilize advanced detection using on-board resonant mass sensors, and other means of mass spectroscopy. Ultimately, this would lead to microfluidic MNS that perform separation, purification and detection of antibodies, aptamers, peptides and metabolic markers.

The panel recommended the following priorities:

a) Horizon 2015:
1. "Impedance" (compatibility) matching (materials and muscle, photoreceptor-electrode)
2. Surface, sample preparation (isolation of bacteria from blood, virus for CD4)
3. Sample preparation for surfaces, anti-fouling phenomena (basic issue: how does it occur?), coatings
4. Capture of circulating tumor cells from whole blood
5. Neuromorphic circuits

b) Horizon 2025:
1. Multi-cellular, organ technologies (e.g., tissue and vessels)
2. Advanced strategies for powering systems (self or body powered)
3. Super-capacitors, biocompatible batteries, beyond photovoltaic methods
4. Cellular matrix, neural regenerative circuits, neural wiring

c) Horizon 2040:
1. Robustness, intelligence (e.g., implantable devices able to last a lifetime)
2. Repair, regeneration and replacement
3. Implanting functional spinal cord, brain tissue
4. Mature biotic/abiotic interface

Infrastructure Monitoring and Homeland Security

There is an obvious role for MNS in monitoring civil infrastructure – with respect to both reliability and security. The needs are vast, and include, for example, MNS for monitoring:

- Transportation infrastructure: bridges, roadways, railways, tunnels, shipping docks, levees, aviation;
- Public spaces: office buildings, schools, shopping malls, cinema theaters, sports stadiums, airports, train stations;
- Utilities: electrical grids, power plants, water works, sewage systems, oil and gas pipelines;
- Communication infrastructure: telephone, internet, TV, and radio.

Unfortunately, the infrastructure in the U.S. is aging. A report by the American Society of Civil Engineers estimates a need for about $2.2 trillion in investment in the coming 5-year period. The vision is that amongst other things, MNS can contribute to distributed sensing systems by providing power-efficient sensors, wireless communications, and integration into cyber-physical systems that provide awareness, data driven decision-making, and rapid response. MNS can be potentially embedded within structural materials, providing security, safety, and long-term savings through the avoidance of failures. The panel recommended the following the following items, amongst others:

a) Horizon 2015:
1. High sensitivity/selectivity sensors and systems for water, air, and food monitoring
2. Application of reliable sensor systems to infrastructure
3. Sensors and packaging for harsh environments relevant to infrastructure
4. Low-power wireless communication with deployed systems – devices, algorithms, and protocols
5. Energy harvesting
6. Efficient data compression and sparsification algorithms that deal with the voluminous raw sensor data

b) Horizon 2025:
1. Sensor-informed decision analysis systems
2. Low-cost ultra-miniature analysis systems
3. Mobile sensing systems
4. Damage precursor identification and safe-life-remaining models
5. Integrative sensor/structural models
6. Data fusion combining sensor input and health/usage monitoring

c) Horizon 2040:
1. Cyber-physical systems
2. Seamless integration into infrastructure
3. Extremely remote sensors

Energy/Power

As noted previously, the focus of the energy/power topical panel was to determine the potential for MNS to contribute to macro-scale needs in society. Total power usage in the world is presently on the order of 15 terawatts. It is expected to more than double by 2040 because of increasing industrialization and growing populations. There were two general questions of posed to the panel. First, with regard to MNS for power conversion, which of the currently emerging approaches might be translated, in a cost-efficient manner, to meet macro-scale power needs? Is it possible to scavenge sufficient power (for example, from vibration, RF radiation, or thermal gradients) to serve the minimal needs of a family unit, perhaps in a developing nation? A successful solution would provide high energy density, and means of scaling up production. Second, how can MNS help to improve efficiency of conventional and emerging methods of power generation, distribution, and storage? Are there ways to use MNS to improve the performance of solar photovoltaic cells, thermoelectric converters, or ionic and proton exchange fuel cells? What are the ways by which MNS can be employed to improve the efficiency of existing power plants, or to reduce energy consumption?

The panel recommended the following priorities:

a) Horizon 2015:

1. System level analysis over the full life cycle for generation, harvesting, use, and energy storage categories
2. Fundamental research in energy materials/systems
3. Heterogeneous materials integration into systems
4. Power conversion for micro-systems that is scalable to the macro-scale needs
5. Energy efficient sensor networks for efficient energy usage (Smart Grid)

b) Horizon 2025:

1. Fabrication of systems for mass production
2. Heterogeneous integration, including the bio/machine interface
3. New methods of harvesting and converting energy
4. Capture energy cascade

c) Horizon 2040:

1. Energy amplification to convert low potential energies to high potential (low quality to high quality)
2. Broad research in energy materials/systems

In reviewing the scope, vision, and status of research in MNS, it appears clear that these technologies are poised for major societal impact in all four topical domains: environmental monitoring; health care; infrastructure monitoring/homeland security; and energy/power. The research challenges and trajectories differ to some extent by topical domain, but there are also overlapping needs. As research progresses in these domains, a systems-oriented perspective can help to keep efforts focused, maximizing societal gain for the available resources. Practical and affordable solutions will require interdisciplinary work toward engineered MNS. Partnerships between specialists, and between academia and industry will dictate success.

2. Participant Support

According to the proposal submitted to the NSF, panelists who participated in the full-day MNS Horizon 2040 Workshop and presenting student authors from US Academic Institutions at the associated Transducers 2009 Conference were supported. Panelists received a flat-rate stipend, students/postdocs a partial travel support. The student/post-doc travel support was limited to students who were representing US universities and the available travel funds were equally distributed among qualified student/postdoc applicants. Both, panelists and students/postdocs had to submit supporting documentation as required by the policies of the Georgia Institute of Technology.

Overall, 43 of the 45 panelists participating in the Workshop received the flat-rate stipend. The list of the supported panelists is given in Table 1.

Name	Institution
	MIT
	Texas A&M
	Duke University
	University of Illinois
	Cornell University

	University of Washington
	Wako Diagnostics
	Georgia Institute of Technology
	University of Utah
	University of Illinois
	University of Washington
	University of California, Davis
	Carnegie Mellon University
	University of Sherbrooke
	University of Maryland
	University of Wisconsin
	University of California, Santa Barbara
	University of California, Los Angeles
	University of Southern California
	University of California, Berkeley
	Columbia University
	University of California, Irvine
	University of Southern California
	University of California, Berkeley
	U. of Nebraska
	Virginia Tech
	University of Cambridge, UK
	University of Illinois
	Goodrich
	Dartmouth College
	Kyoto University, Japan
	Caltech
	Johns Hopkins University
	University of Freiburg, Germany
	Georgia Institute of Technology
	Louisiana Tech University
	University of Florida
	Case Western Reserve University
	University of Michigan
	University of Texas – Austin
	Boston University
	Purdue University

Table 1: Workshop panelists supported by flat-rate stipend.

In addition, the grant by the National Science Foundation allowed for travel support to 90 students/postdocs representing 30 US academic institutions. The supported students/postdocs and their institution are listed in Table 2.

	Last Name	**First Name**	**Institution**
1			University of California, Berkeley
2			University of Michigan
3			Virginia Tech

4			University of Minnesota
5			University of Florida
6			University of California, Berkeley
7			Northeastern University
8			Stanford University
9			Stanford University
10			University of Southern California
11			University of Wisconsin, Madison
12			Arizona State University
13			University of Texas, Dallas
14			University of Washington
15			California Institute of Technology
16			University of Michigan
17			California Institute of Technology
18			Carnegie Mellon University
19			University of California, Los Angeles
20			Louisiana Tech
21			University of Washington
22			University of Michigan
23			University of Michigan
24			University of Southern California
25			Georgia Institute of Technology
26			University of Washington
27			University of Texas, Austin
28			University of California, Berkeley
29			University of California, Berkeley
30			Northwestern University
31			University of California, Los Angeles
32			California Institute of Technology
33			Columbia University
34			University of Minnesota
35			Stanford University
36			Georgia Institute of Technology
37			Case Western Reserve University
38			Columbia University
39			Georgia Institute of Technology
40			University of Michigan
41			University of Pennsylvania
42			University of California, Los Angeles
43			Louisiana State University
44			Case Western Reserve University
45			University of Cincinnati
46			University of Southern California
47			University of California, Berkeley
48			Carnegie Mellon University
49			Stanford University
50			Georgia Institute of Technology

51			University of Michigan
52			California Institute of Technology
53			University of Minnesota
54			University of California, Irvine
55			Massachusetts Institute of Technology
56			University of Michigan
57			Georgia Institute of Technology
58			University of California, Berkeley
59			Georgia Institute of Technology
60			University of California, Los Angeles
61			Columbia University
62			Drexel University
63			Georgia Institute of Technology
64			Pennsylvania State University
65			Arizona State University
66			Stanford University
67			University of Pennsylvania
68			University of California, Irvine
69			University of California, Irvine
70			California Institute of Technology
71			University of Pennsylvania
72			University of California, Berkeley
73			Georgia Institute of Technology
74			University of California, Berkeley
75			Georgia Institute of Technology
76			University of California, Irvine
77			Stanford University
78			University of Michigan
79			Cornell University
80			University of Florida
81			Arizona State University
82			Georgia Institute of Technology
83			Arizona State University
84			Virginia Tech
85			University of Wisconsin, Madison
86			University of Minnesota
87			Johns Hopkins University
88			University of Wisconsin, Madison
89			Arizona State University
90			University of Michigan

Table 2: Students/postdocs with institution receiving partial travel support.

3. References

1. Y. Gianchandani, "Emerging research in micro and nanosystems: opportunities and challenges for societal impact," *Proceedings of SPIE, vol. 7593, 2010*, 759302-1-8.